Long-term evolution of fracture permeability in slate as potential target reservoirs for EGS

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MEET Project WP5, Task 5.1: Characterization of the four Variscan Reservoir types:
(6) Long-term sustainability of fractured rock system based on laboratory experiments (GFZ)
Properties:
- Geological properties (e.g., faults, stress field, rock types)
- Thermophysical rock properties (e.g., thermal conductivity, heat capacity)
- Hydraulic properties (e.g., fracture permeability)
- Fluid properties (e.g., density, viscosity, ions)

Indicators that guarantee the success of an EGS project:
reservoir aspects
- Temperature (depends on area and depth)
- Flow rate (can be controlled and enhanced!)

EGS diagram (source: DOE, Geothermal Technologies Program)
Geographical diversification for EGS

Granitic/crystalline rocks
Sedimentary rocks
Metamorphic rocks* (this study)

Enlarge potential areas for installation of new capacities.
High/medium temperatures can be found in various contexts and their production can be enhanced by EGS.
Scientific / engineering problems

An abundant heat source (energy)
Fluid circulations (media for heat extraction)
Permeable pathways (fracture networks within target reservoirs)

Sustainability!! (the success of the project and investment)
  • Fracture closure*
  • Scaling
  • Corrosion

Main task: demonstrate long-term fracture sustainability of fractured rocks based on laboratory experiments.

laboratory time scale (weeks & months) vs. in-situ time scale (years & decades)

Better understanding

Deep Geothermal Reservoir Groß Schönebeck

Motivations

Blöcher et al. 2016 (Geothermics)
Potential mechanisms

Fracture sustainability mediated by fluid-rock interactions

- Stress corrosion
- Pressure solution
- Dissolution at free walls
- Mineral precipitation
Experimental Procedures

Saw-cut slate fractures

Flow-through experiments were conducted to investigate the effects of flow, temperature, and time-dependent fluid-rock interactions on fracture permeability.

Identical fracture samples:

- SM1 → 90 °C
- SM2 → 70 °C

Workflow for the long-term experiments conducted at GFZ. Fractured slate samples (a) are assembled (b) and tested at simulated reservoir conditions (c).
Experimental Tasks

Three main tasks:

1. Initial continuous flow tests (the influence of flow dynamics)
2. Cyclic temperature up to 70 °C or 90 °C (simulation of production and injection temperatures)
3. Intermittent flow-through tests for > one month (effects of chemical reactions)

Flow-through measurements

• Pc: 10 MPa, Pp: 1 MPa
• Fluid type: deionized water
• Time interval of stopped flow: 6 days
• Hydraulic aperture is determined based on the “cubic law”.
  \[ a_h = \sqrt[3]{\frac{12Q\mu L}{W \cdot \Delta P}} \]
• Effluent samples were measured with ICP-OES
1. Continuous flow-through tests at room temperature

- Sample permeability first continuously decreases after pressurization, but progressively converges within about three days.
2. Cyclic temperature up to 70 °C or 90 °C

- Increasing temperature leads to an additional permeability decline that is irreversible.
3. Time-dependent intermittent flow

- Time-dependent permeability reduction is more pronounced at 90 °C in comparison to that at 70 °C, but both samples show a negligible decline with time at room temperature after cooling.
Topographies of the grinding fracture surfaces before and after the experiments

### Initial Hydraulic aperture $a_h$ at room temperature (25 °C)

- SM1: 7.48 µm
- SM2: 7.72 µm

### Final Hydraulic aperture $a_h$ at room temperature (29 °C)

- SM1: 3.49 µm (up to 90 °C) - 53%
- SM2: 5.65 µm (up to 70 °C) - 27%

<table>
<thead>
<tr>
<th>Sample</th>
<th>Max diff. (µm)</th>
<th>Average mean (µm)</th>
<th>Root-mean-square (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM1_SurfaceA</td>
<td>41</td>
<td>2.3</td>
<td>2.9</td>
</tr>
<tr>
<td>SM2_SurfaceA</td>
<td>70</td>
<td>1.4</td>
<td>2.1</td>
</tr>
<tr>
<td>SM1_SurfaceA</td>
<td>45</td>
<td>3.5</td>
<td>4.3</td>
</tr>
<tr>
<td>SM2_SurfaceA</td>
<td>35.1</td>
<td>3.5</td>
<td>4.5</td>
</tr>
</tbody>
</table>
Images of fracture surfaces

- For SEM analyses

SM1: Surface A_before

SM1: Surface A_after

SM2: Surface A_before

SM2: Surface A_after
Fluid chemistry analyses

<table>
<thead>
<tr>
<th>Minerals</th>
<th>Content (%)</th>
<th>Composition</th>
<th>Ions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>22.70</td>
<td>SiO2</td>
<td>Si</td>
</tr>
<tr>
<td>Calcite</td>
<td>8.34</td>
<td>CaCO3</td>
<td>Ca</td>
</tr>
<tr>
<td>Dolomite</td>
<td>16.44</td>
<td>CaMg(CO3)2</td>
<td>Ca, Mg</td>
</tr>
<tr>
<td>Muscovite</td>
<td>12.81</td>
<td>KAl2[AlSi3O10(OH)2]</td>
<td>K, Al, Si</td>
</tr>
<tr>
<td>Illite</td>
<td>16.43</td>
<td>K0.65Al2[Al0.65Si3.35O10(OH)2]</td>
<td>K, Al, Si</td>
</tr>
<tr>
<td>Chlorite (group)</td>
<td>17.10</td>
<td>(Mg,Fe++)5Al[Si3Al]O10(OH)8</td>
<td>Mg, Fe, Al, Si</td>
</tr>
<tr>
<td>Feldspar (group)</td>
<td>5.72</td>
<td>(Na,K)AlSi3O8</td>
<td>Na, K, Al, Si</td>
</tr>
</tbody>
</table>

Data from Göttingen team

Potential mechanisms
- Mineral dissolution/precipitation (at free walls)
- Pressure solution (at contact asperities)
- Cation exchanges (clay minerals)
  - Divalent ions $\rightarrow$ monovalent ions

GFZ geochemistry lab
In-situ fluid inclusions within slates are mainly composed of water with low salinity: NaCl and CaCl2. In contrast to the deionized water used in this study, natural brines may lead to different fracture closure behaviour due to fluid chemistry.

**Fluid inclusions**

<table>
<thead>
<tr>
<th>Fluid inclusion type</th>
<th>Composition</th>
<th>Host</th>
<th>CH₄ mol%</th>
<th>CO₂ mol%</th>
<th>N₂ mol%</th>
<th>Total salinity wt.% NaCl eq.</th>
<th>NaCl (wt%)</th>
<th>CaCl₂ (wt%)</th>
<th>H₂O (wt%)</th>
<th>Homogenization temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>primary</td>
<td>H₂O-NaCl</td>
<td>Qtz</td>
<td>0</td>
<td>0 - 2.1*</td>
<td>---</td>
<td>0</td>
<td>100</td>
<td>---</td>
<td>---</td>
<td>148 (L) - 372 (V)</td>
</tr>
<tr>
<td>primary</td>
<td>H₂O-CaCl₂-NaCl</td>
<td>Qtz</td>
<td>0.3 - 100*</td>
<td>0 - 1.7*</td>
<td>(10)**</td>
<td>19 - 32</td>
<td>2 - 8</td>
<td>14 - 25</td>
<td>72 - 82</td>
<td>98 (L) - 243 (L)</td>
</tr>
<tr>
<td>primary</td>
<td>H₂O-NaCl</td>
<td>Qtz</td>
<td>1 - 4</td>
<td></td>
<td>96 - 99</td>
<td>105 - 260</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>primary</td>
<td>H₂O-NaCl</td>
<td>Qtz</td>
<td>2 - 3</td>
<td></td>
<td></td>
<td></td>
<td>97 - 98</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>primary</td>
<td>H₂O-CaCl₂-NaCl</td>
<td>Calcite</td>
<td>12 - 30</td>
<td>7 - 16</td>
<td>5 - 12</td>
<td>77 - 87</td>
<td>103 (L) - 262 (L)</td>
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<tr>
<td>primary</td>
<td>H₂O-NaCl</td>
<td>Qtz</td>
<td>0 - 5</td>
<td></td>
<td>94 - 100</td>
<td>139 (L) - 262 (L)</td>
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<tr>
<td>primary</td>
<td>CH₄-N₂</td>
<td>Qtz</td>
<td>1 - 5</td>
<td></td>
<td>95 - 99</td>
<td>137 (L) - 362 (L)</td>
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<td>H₂O-NaCl</td>
<td>Qtz</td>
<td>1 - 4</td>
<td></td>
<td>96 - 99</td>
<td>150 (L) - 242 (L)</td>
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<tr>
<td>primary</td>
<td>H₂O-NaCl</td>
<td>Qtz</td>
<td>2 - 4</td>
<td></td>
<td>96 - 98</td>
<td>142 (L) - 178 (L)</td>
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</tr>
</tbody>
</table>

Data from Göttingen team
Conclusions

• Fluid-rock interactions cause partial fracture closure, which is irreversible.

• Temperature increase could accelerate fluid-rock interactions, which are negative to fracture aperture sustainability.

• Natural brine circulation may cause different fracture deformation behaviours due to various ions, which needs to be investigated.
What learnt from the preliminary results

• Isn’t slate suitable for an EGS?
  • The current experiments only show the results of fractures in several microns, larger fractures (e.g., natural tensile fractures, high roughness fractures) may exhibit different behaviours.
  • Natural brine contains different ions that may reach chemical equilibrium, and thus fluid-rock interactions could be decelerated.
  • Needs more investigations.

Next step:
  o Flow-through experiments with prepared brines (e.g., NaCl solutions)
  o Continuous strain measurements during flow-through experiments
Thank you very much for your attention

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